

A STUDY OF THE CONSTRAINED VAPOR BUBBLE THERMOSYPHON

SUMMARY OF RESEARCH REPORT FOR NAG3-1834
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1. INTRODUCTION

The objective of this effort is to better understand the physics of evaporation, condensation, and fluid flow as they affect the heat transfer processes in a constrained vapor bubble heat exchanger (CVBHX). This CVBHX consists of a small enclosed container with a square cross section (inside dimensions: 3 x 3 x 40 mm) partially filled with a liquid. The major portion of the liquid is in the corners, which act as arteries. When a temperature difference is applied to the ends of the CVBHX, evaporation occurs at the hot end and condensation at the cold end resulting in a very effective heat transfer device with great potential in space applications. Liquid is returned by capillary flow in the corners. A complete description of the system and the results obtained to date are given in the papers listed below.

Near-term flight experimental concepts were developed to pursue both equilibrium and non-equilibrium testing of the CVBHX operation. Flight-qualified apparatus and optical instrumentations were designed and developed. The microscopic intermolecular force (pressure) field, which is a function of the liquid film thickness profile, were measured using microcomputer enhanced video microscopy based on interferometry. Models of the transport processes in the contact line region of a CVBHX which include the effects of liquid-solid and liquid-vapor intermolecular forces were further developed. The augmented Young-Laplace equation over a large range of film thickness was evaluated. The overall heat conductance of the CVBHX as a function of liquid volume and heat flow rate were determined.

This study is synergistic in that the space program needs passive systems like the CVBHX for thermal control and research on a CVBHX requires a microgravity environment. This study is also multi-faceted: (1) It is a basic study in interfacial physics because the CVBHX is used to measure the dispersion constant which characterizes the interfacial intermolecular force field; (2) It is a basic study in fluid physics because it evaluates fluid flow in ultra-thin liquid films; (3) It is a dynamic study in thermal transport because it evaluates the heat transfer capabilities of a small scale heat exchanger; and (4) the study of a heat exchanger which can also be called a wickless heat pipe. The results from this study are not only applicable to space applications, but can also help the design of conventional heat pipes which are poorly understood.

The initial studies used the pentane/glass system which was oriented horizontal with asymmetric flow fields. To obtain axisymmetric flow fields, a new experimental system using a vertical CVBHX cell was built and used to evaluate an additional fluid. Ethanol was tested as a potential partially wetting candidate and found that it does act sufficiently different to warrant its inclusion as a second fluid in the flight experiments. With ethanol, a boiling phenomena can be observed near the contact line. Ethanol has a finite contact angle and a dry region, and the contact line oscillates more readily than pentane. In addition, a region of dropwise condensation, which is indicative of a partially wetting fluid, can be observed at low heat fluxes. This region of dropwise condensation and the easy propensity to boil were not observed with pentane. The results using ethanol were obtained using a vertical cell which gives an axisymmetric system. Therefore, a complete numerical comparison with our previous results cannot be made at this time because the axial pressure gradient in the vertical cell is affected by the earth's gravitational field, which is not the case with the previously used horizontal cell with pentane. The disadvantage of the horizontal cell is that the system is asymmetric.

We found that the use of ethanol as a partially wetting second fluid would enhance the observations and measurements associated with contact line instabilities, boiling and dryout. Significant additional data would be obtained for the comparison of the behavior of partially wetting and completely wetting fluids. On the other hand, additional tests would have to be done during the microgravity flight and additional preparation for the flight would also have to be done. From the PI's point-of-view, these tests are desirable but also require additional resources and flight time.

This final report represents a transition to a new grant in which additional ground-based research and development work to support a flight experiment on the International Space Station was funded for the five year period starting April 22, 2000. Assistance with the development work for the flight experiment itself at the NASA Glenn Research Center along with necessary basic ground-based research and post flight analyses of the data are envisioned. We had our Requirements Definition Review on December 8, 1998. The new work is needed to accomplish the science requirements and test matrix outlined in our revised Science Requirements Document (60055-DOC-000) dated October, 1999, and to extend the fundamental understanding of interfacial transport processes of use in microgravity.

One of our graduate students (Ms. Sumita Basu), who is currently at FDC, has been a great help in coordinating the work at NASA, FDC, and RPI. She is doing her thesis using the actual hardware being designed and built for the Flight Experiment. This is essential because the actual heat transfer cell has to fit into the space available in the LMM. In addition, she is using the vacuum chamber at NASA (which we do not have) to determine the effect of radiation heat transfer in the absence of convection on the temperature profile in the cell. The work at FDC is going well.

The Principle Investigator was the recipient of the 1998 Donald Q. Kern Award at the 1999 National Heat Transfer Conference in recognition of his heat transfer studies. Many of these studies were associated with the acknowledged CVB Program supported by NASA.

CONCLUSIONS

- Based on viscous losses in the corners, the maximum attainable axial heat flow rate increases with the cube of the characteristic width of the non-equilibrium CVBHX.
- Based on viscous losses in the corners, the maximum attainable axial heat flux increases linearly with the characteristic width of the CVBHX.
- Low capillary pressure systems (relatively large widths) are desirable heat transfer systems.
- Microgravity allows the axisymmetric study of a larger range of heat fluxes and low capillary pressure systems, which have large characteristic widths.
- The effects of stability, oscillations, and cavitation in the thin film region on the maximum attainable heat flux are unknown.
- To enhance the understanding of passive, change-of-phase, high heat flux, low capillary pressure systems, the CVBHX should be studied under microgravity conditions.

- Therefore, extensions of our current studies of the non-equilibrium CVB to a microgravity environment are desirable to obtain "axisymmetric" profiles which will give a more definitive understanding of high flux, passive, change-of-phase systems.
- Both completely wetting (pentane) and partially wetting (ethanol) systems should be studied.

II. PAPERS & PRESENTATIONS

JOURNALS:

- J1) Wayner, P. C., Jr., "Constrained Vapor Bubble," *Microscale Thermophysical Engineering*, Vol. 1, pp. 111-118, 1997.
- J2) Karthikeyan, M., Huang, J., Plawsky, J., and Wayner, P. C., Jr., "Experimental Study and Modeling of the Intermediate Section of the Non-isothermal Constrained Vapor Bubble," *ASME J. of Heat Transfer*, Vol. 120, pp 166-173, 1998.
- J3) Wayner, P. C., Jr. "Intermolecular Forces in Phase-Change Heat Transfer: Kern Award Review", *AIChE Journal*, Vol. 45, pp 2055-2068, 1999.
- J4 Huang, J., Karthikeyan, M., Wayner, P. C., Jr., and Plawsky, J. L., "Heat Transfer and Fluid Flow in a Nonisothermal Constrained Vapor Bubble" *Chemical Engineering Communications*, Vol.181, pp203-223, 2000.
- J5 Wang, Y- X, Plawsky, J. L., and Wayner, P. C., Jr., "Optical Measurement of Microscale Transport Processes in Dropwise Condensation", Accepted for publication in *Microscale Thermophysical Engineering*.

SCIENCE CONCEPT REVIEW & SCIENCE REQUIREMENTS DOCUMENT

Plawsky, J. and Wayner, P. C., Jr., "Science Requirements Document for Constrained Vapor Bubble" *Science Concept Review*, NASA Lewis Research Center, Cleveland, OH, September 16, 1997.

Plawsky, J. and Wayner, P. C., Jr., "Science Requirements Document for Constrained Vapor Bubble" NASA RDR PUBLICATION, CVB-000, NASA Lewis Research Center, Cleveland, OH, December 8, 1998. Revised October, 1999.

PROCEEDINGS:

- P1) Karthikeyan, M., Huang, J., Plawsky, J., and Wayner, P. C., Jr., "Experimental Study and Modeling of the Adiabatic Section of the Constrained Vapor Bubble Heat Exchanger," Proceedings of the Space Technology and Applications International Forum, Albuquerque, NM, January 26-30, 1997 (AIP Conference Proceedings 387, Part 2, First Conference on Applications of Thermophysics in Microgravity, Space Technology and Applications International Forum -1997, pp 641-646, Ed. Mohamed S. El-Genk).
- P2) Karthikeyan, M., Huang, J., Plawsky, J., and Wayner, P. C., Jr., "Initial Nonisothermal Experimental Study of the Constrained Vapor Bubble Thermosyphon," HTD-Vol. 327, 1996 National Heat Transfer Conference, Vol. 5, ASME 1996, pp 121-129. (experimental results from NASA NAG3-1399).
- P3) Karthikeyan, M., Huang, J., Plawsky, J. L, and Wayner, P. C., Jr., "Experimental Study of the Constrained Vapor Bubble Thermosyphon", *Third Microgravity Fluid Physics Conference*, NASA Lewis Research Center, Cleveland, OH, June 13-15, 1996, NASA Conference Publications 3338, pp. 147-152.
- P4) Wayner, P. C., Jr., "Constrained Vapor Bubble," Preprint at the U.S.-Japan Joint Seminar on Molecular and Microscale Transport Phenomena, Santa Barbara, CA, August 7-10, 1996.
- P5) Karthikeyan, M., Huang, J., Plawsky, J., and Wayner, P. C., Jr., "Experimental Study and Modeling of the Intermediate Section of the Non-isothermal Constrained Vapor Bubble," Proceedings of the 2nd Joint China/USA Chemical Engineering Conference, Beijing, China, May 19-22, 1997, Vol.1, pp. 339-342.

- P6) Science Concept Review Documents, NASA Lewis Research Center, Cleveland, OH, September 16, 1997.
- P7) Huang, J., Karthikeyan, M., Plawsky, J., and Wayner, P. C., Jr., "Two-Dimensional Analysis of the Evaporator of a Constrained Vapor Bubble" Preprints 10th International Heat Pipe Conference, Stuttgart, Germany, September 22-26, 1997, Preprint Paper # F5.
- P8) Huang, J., Karthikeyan, M., Plawsky, J., and Wayner, P. C., Jr., "Experimental Study and Modeling of the Effect of Low-Level Impurities on the Operation of the Constrained Vapor Bubble," Space Technology and Applications Forum (STAIF-98), January 25-29, 1998, Albuquerque, NM., , AIP Conference Proceedings 420, Part I, pp. 446-451.
- P9) Huang, J., Karthikeyan, M., Plawsky, J. L, and Wayner, P. C., Jr., " Constrained Vapor Bubble ", Fourth Microgravity Fluid Physics Transport Phenomena Conference, NASA Lewis Research Center, Cleveland, OH, August 12-14, 1998.
- P10) Huang, J., Karthikeyan, M., Plawsky, J. L, and Wayner, P. C., Jr., " Constrained Vapor Bubble Heat Exchanger", Proceedings of 11th International Heat Transfer Conference, J. S. Lee, Editor, 1998 Korean Society of Mechanical Engineers, August 23-28, 1998, Kyongju, Korea, Vol. 6, pp. 267-272.
- P11) Wayner, P. C., Jr., "Interfacial Heat Transfer: Theory and Experiment," 1998 AIChE Heat Transfer and Energy Conversion Division Award Seminar, 1998 Annual AIChE Meeting, Paper 190 b, Miami Beach, FL, November 15-20, 1998.
- P12) Plawsky, J. and Wayner, P. C., Jr., "Constrained Vapor Bubble (CVB) Science Requirements Document" NASA RDR PUBLICATION, CVB-000, NASA Lewis Research Center, Cleveland, OH, December 8, 1998.
- P13) Plawsky, J. and Wayner, P. C., Jr. "Long Range Intermolecular Forces in Change of Phase Heat Transfer: The Constrained Vapor Bubble", Microgravity Fluid Physics and Heat Transfer, Engineering Foundation Conference, Turtle Bay, Oahu, Hawaii, September 19- 24, 1999

P14) Wayner, P. C., Jr. "Long Range Intermolecular Forces in Change of Phase Heat Transfer: (1998 Donald Q. Kern Award Review)", 1999 National Heat Transfer Conference, Paper # 320, Albuquerque, NM, August 15-17, 1999, ASME, NY, NY.

P15) Huang, J., Plawsky, J., and Wayner, P. C., Jr., " Modeling Transport Processes in a Constrained Vapor Bubble Under Microgravity Conditions," Proceedings of the Space Technology and Applications International Forum (STAIF-2000), Albuquerque, NM, January 30-February 3, 2000 (AIP Conference Proceedings 504, , Space Technology and Applications International Forum -2000, pp 261-272, Ed. Mohamed S. El-Genk).

P16) Basu, S., Plawsky, J. L., and Wayner, P. C., Jr., "Initial Thermal Modeling of the Constrained Vapor Bubble Heat Exchanger Using TSS/SINDA" , Proceedings of Thermal and Fluids Analysis Workshop 2000 (TFAWS 2000), Cleveland, OH, August 20-21, 2000.

P17) Wang, Y-X, Plawsky, J. L., and Wayner, P. C., Jr. "Heat and Mass Transfer in a Vertical Constrained Vapor Bubble Heat Exchanger Using Ethanol", 34th National Heat Transfer Conference, Paper # NHT2000-12201, Pittsburgh, PA, August 15-17, 2000, ASME, NY, NY.

PRESENTATIONS:

PR1) Karthikeyan, M., Huang, J., Plawsky, J. L., and Wayner, P. C., Jr., "Experimental Study of the Constrained Vapor Bubble Thermosyphon", Third Microgravity Fluid Physics Conference, NASA Lewis Research Center, Cleveland, OH, June 13-15, 1996.

PR2) Karthikeyan, M., Huang, J., Plawsky, J., and Wayner, P. C., Jr., "Initial Nonisothermal Experimental Study of the Constrained Vapor Bubble Thermosyphon," 1996 National Heat Transfer Conference, Houston, TX, August, 1996. (experimental results from NASA NAG3-1399)

PR3) Wayner, P. C., Jr., "Constrained Vapor Bubble," U.S.- Japan Joint Seminar Molecular and Microscale Transport Phenomena, Santa Barbara, CA, August 7-10, 1996.

PR4) Karthikeyan, M., Huang, J., Plawsky, J., and Wayner, P. C., Jr., "Experimental and Theoretical Analysis of the "Adiabatic" Region in a Constrained Vapor Bubble Thermosyphon," 1996 Annual Meeting of the A.I.Ch.E., Chicago, IL, Nov., 1996.

PR5) Science Concept Review, NASA Lewis Research Center, Cleveland, OH, September 16, 1997.

PR6) Karthikeyan, M., Huang, J., Plawsky, J., and Wayner, P. C., Jr., "Experimental Study and Modeling of the Adiabatic Section of the Constrained Vapor Bubble Heat Exchanger," Space Technology and Applications Forum (STAIF-97) (First Conference on Applications of Thermophysics in Microgravity), Albuquerque, NM, January 26-30, 1997 .

PR7) Huang, J., Karthikeyan, M., Plawsky, J., and Wayner, P. C., Jr., "Two-Dimensional Analysis of the Evaporator of a Constrained Vapor Bubble" 10th International Heat Pipe Conference, Stuttgart, Germany, September 22-26, 1997.

PR8) Karthikeyan, M., Huang, J., Plawsky, J., and Wayner, P. C., Jr., "Experimental Study and Modeling of the Intermediate Section of the Non-isothermal Constrained Vapor Bubble," 2nd Joint China/USA Chemical Engineering Conference, Beijing, China, May 19-22, 1997.

PR9) Karthikeyan, M., Huang, J., Wayner, P. C., Jr., and Plawsky, J., "The Effect of Interfacial Phenomena on Transport Processes in a Constrained Vapor Bubble," 1997 Annual Meeting of AIChE, Los Angeles, CA, Nov 16-21, 1997.

PR10) Huang, J., Karthikeyan, M., Plawsky, J., and Wayner, P. C., Jr., "Experimental Study and Modeling of the Effect of Low-Level Impurities on the Operation of the Constrained Vapor Bubble," Space Technology and Applications Forum (STAIF-98), Albuquerque, NM, January 25-29, 1998. , AIP Conference Proceedings 420, Part I, pp. 446-451

PR11) Wayner, P. C., Jr., "Interfacial Heat Transfer: Theory and Experiment," 1998 AIChE Heat Transfer and Energy Conversion Division Award Seminar, 1998 Annual AIChE Meeting, Miami Beach, FL, November 15-20, 1998.

- PR12) Huang, J., Karthikeyan, M., Plawsky, J. L, and Wayner, P. C., Jr., " Constrained Vapor Bubble ", Fourth Microgravity Fluid Physics Transport Phenomena Conference, NASA Lewis Research Center, Cleveland, OH, August 12-14, 1998.
- PR 13) Huang, J., Karthikeyan, M., Plawsky, J. L, and Wayner, P. C., Jr., " Constrained Vapor Bubble Heat Exchanger", 11th International Heat Transfer Conference, August 23-28, 1998, Kyongju, Korea.
- PR 14) Plawsky, J. and Wayner, P. C., Jr., "Constrained Vapor Bubble (CVB) Science Requirements Document" NASA RDR PUBLICATION, CVB-000, NASA Lewis Research Center, Cleveland, OH, December 8, 1998.
- PR15) Wang, Y-X, Basu, S., Plawsky, J., and Wayner, P. C., Jr., "Constrained Vapor Bubble Heat Exchanger", poster for Space Week, Rensselaer Polytechnic Institute, Troy, NY, April 5-11, 1999.
- PR16) Wang, Y-X, Basu, S., Plawsky, J., and Wayner, P. C., Jr., "Constrained Vapor Bubble Heat Exchanger", poster for Inauguration of the Honorable Dr. Shirley Ann Jackson, Rensselaer Polytechnic Institute, Troy, NY, Sept. 22-23, 1999.
- PR 17) Plawsky, J. and Wayner, P. C., Jr. "Long Range Intermolecular Forces in Change of Phase Heat Transfer: The Constrained Vapor Bubble", Microgravity Fluid Physics and Heat Transfer, Engineering Foundation Conference, Turtle Bay, Oahu, Hawaii, September 19- 24, 1999
- PR18) Wayner, P. C., Jr. "Long Range Intermolecular Forces in Change of Phase Heat Transfer: (1998 Donald Q. Kern Award Review)", 1999 National Heat Transfer Conference, Paper # 320, Albuquerque , NM, August 15-17, 1999, ASME, NY, NY.
- PR19) Huang, J., Plawsky, J., and Wayner, P. C., Jr., " Modeling Transport Processes in a Constrained Vapor Bubble Under Microgravity Conditions," Proceedings of the Space Technology and Applications International Forum (STAIF-2000), Albuquerque, NM, January 30-February 3, 2000 (AIP Conference Proceedings 504, , Space Technology and Applications International Forum -2000, pp 261-272, Ed. Mohamed S. El-Genk).

PR20) Wang, Y- X, Plawsky, J. L., and Wayner, P. C., Jr., "Wetting and Partially Wetting Fluid Profiles in a Constrained Vapor Bubble Heat Exchanger", Fifth Microgravity Fluid Physics and Transport Phenomena Conference, Cleveland, OH, August 9-11, 2000.

PR21) Wang, Y-X, Plawsky, J. L., and Wayner, P. C., Jr. "Heat and Mass Transfer in a Vertical Constrained Vapor Bubble Heat Exchanger Using Ethanol", 34th National Heat Transfer Conference, Paper # NHT2000-12201, Pittsburgh, PA, August 15-17, 2000, ASME, NY, NY.

PR22) Basu, S., Plawsky, J. L., and Wayner, P. C., Jr., "Initial Thermal Modeling of the Constrained Vapor Bubble Heat Exchanger Using TSS/SINDA", Thermal and Fluids Analysis Workshop 2000 (TFAWS 2000), Cleveland, OH, August 20-21, 2000.

PR23) Wang, Y- X, Plawsky, J. L., and Wayner, P. C., Jr., "Optical Measurement of Microscale Transport Processes in Dropwise Condensation", United Engineering Foundation Meeting, Banff, Canada, Oct. 15-20, 2000.

EXTENDED ABSTRACTS

EA1) Karthikeyan, M., Huang, J., Plawsky, J. L., and Wayner, P. C., Jr., "Experimental Study and Modeling of the Intermediate Section of the Non-isothermal Constrained Vapor Bubble," Second Joint U.S./China Chemical Engineering Conference, Beijing, China, May 19-22, 1997.

EA2) Wayner, P. C., Jr., "Interfacial Heat Transfer: Theory and Experiment," 1998 AIChE Heat Transfer and Energy Conversion Division Award Seminar, 1998 Annual AIChE Meeting, Miami Beach, FL, November 15-20, 1998.

PhD DISSERTATION PROPOSALS

DP1) Karthikeyan, M., "Experimental and Analytical Investigation of the Non-isothermal Constrained Vapor Bubble," Ph.D. Dissertation Proposal, August, 1996 (internal RPI document).

DP2) Huang, J., "Modeling of Transport Processes in a Constrained Vapor Bubble," Ph.D. Dissertation Proposal, August, 1996 (internal RPI document).

DP2) Wang, Y-X, "A Study of the Vertical Constrained Vapor Bubble Heat Exchanger," Ph.D. Dissertation Proposal, December, 1999 (internal RPI document).

DOCTORAL THESES

TD1) Karthikeyan, M., "Experimental and Analytical Investigation of the Non-isothermal Constrained Vapor Bubble," Ph. D. Thesis, Rensselaer Polytechnic Institute, Troy, NY, October, 1997.

TD2) Huang, Jianming, "Modeling and Transport Processes in a Constrained Vapor Bubble", Ph. D. Thesis, Rensselaer Polytechnic Institute, Troy, NY, December, 1998.